An Arctic Ice/Ocean Coupled Model with Wave Interactions

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LONG-TERM GOALS

The overarching long-term goal of project N00014-131-0279 remains as defined in the original proposal, namely to include two-dimensional (2D) ocean surface wave interactions with sea ice in a contemporary 3D Arctic ice/ocean model. To accomplish this primary goal, the objectives listed in the next section will be achieved during the journey. Consequential to the primary goal, we aim to

– develop an improved parametrization of how ocean waves and sea ice interact, for use in operational models of the Arctic Basin and the adjacent seas;
– improve the forecasting capacities of contemporary Arctic climate models.

OBJECTIVES

To make progress with our long-term goals, we will

– further our understanding of the hydrodynamical interactions between polar oceans and sea ice;
– model the attenuation and spreading of directional seas within and in the waters adjoining the marginal ice zone (MIZ), using a conservative, multiple wave scattering approach in a medium with random geometrical properties that is specified by means of remote sensing data products and other applicable data sets;
– devise a parametrization of directional wave spreading in the presence of sea ice, to be integrated into operational wave and ice/ocean models, and refine the existing parametrization of ocean wave attenuation to one based on 2D multiple scattering as opposed to a 1D paradigm constrained to the primary wave vector;
– model the effect of realistic ocean wave spectra on the structural integrity of the Arctic ice cover;
– advance new parametrizations for dissipative mechanical processes within the MIZ, to account for additional energy loss not captured by conservative wave scattering theory;
– validate the efficacy of the parametrizations mentioned above using experimental data from past and upcoming field and laboratory work, as available; and
– in association with Professor Hayley Shen, a PI on the same DRI, use the wave scattering model to

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calibrate viscoelastic-type models that render the MIZ as a continuum.

The work described in this report is the outcome of a collaboration between the PI; the two AIs, Bennetts and Williams; and Montiel and Mosig, who are respectively the postdoctoral fellow and new doctoral student on the project, located with the PI at the University of Otago.

APPROACH

Two complementary methodologies to modeling the effects of ocean waves in the Arctic ice-covered ocean are actively being investigated in the 'Sea State and Boundary Layer Physics of the Emerging Arctic Ocean' DRI. The aim of the first approach is to improve the accuracy of present-day operational ice/ocean models by directly including the influential contribution that ocean waves make in reshaping the Arctic ice-covered ocean. In a nutshell, waves break up the sea ice differentially to create the floe size distribution (FSD), thereby allowing individual floes more freedom to move laterally under the action of winds, currents and the waves themselves. This dynamical process affects the proximate concentration and therefore enhances positive ice-albedo temperature feedback by bringing warmer water in contact with the decaying ice mass. In tandem, aggregated fetch length may be increased, which raises the possibility of wave generation within the compass of the ice field. What is more, the presence of this mélange of ice floes influences the way ocean waves propagate in the Arctic Ocean. Dissipative processes and scattering attenuate ocean wave spectra and modify their directional spread. Being the primary focus of the current project, we are developing innovative methods to model these phenomena for realistic wave spectra and FSDs, and are generating averaged parametrizations of their effects for integration in operational models.

The second approach involves substantially improving the way in which sea ice is treated in contemporary third generation operational wave models such as WAVEWATCH® III or WAM, to remedy their existing simplistic parametrization with respect to sea ice. Such models do not resolve phase and are referred to as spectral models. In regard to sea ice, it is planned to render the inhomogeneous ice cover as a surface-floating viscoelastic layer which amasses the physical properties of the ice/water continuum into a single complex compliance that affects the passage of wave energy flux (e.g. Wang and Shen, 2010, 2011, noting that the magnitudes of the viscoelastic moduli are undetermined). This model provides a unified approach to the parametrization of ocean wave dynamics for different types of ice terrains and is therefore a prospective candidate for the 'grid cells' in operational wave models that are either partially or wholly ice-covered. Rogers (2014) has already made some progress but the main challenge will always be to find the relationship between a specific type of ice cover, invariably observed by a satellite passive microwave or SAR sensor, and the corresponding viscoelastic moduli. Our involvement in this work therefore relates to the calibration of the moduli by means of our model, which can accommodate a wide range of ice covers.

Some of the seeding work on project N00014-131-0279 was done under the aegis of WIFAR (Waves-in-Ice Forecasting for Arctic Operators), a partnership between the Nansen Environmental and Remote Sensing Center (NERSC) in Norway and the University of Otago that partly supported one of the AIs (Williams) financially until early 2014. Work started during WIFAR, concerned with the assimilation of wave dynamics into an ice/ocean model of the Fram Strait, was completed with the publication of two papers by Williams et al. (2013a,b) in a special edition of the journal *Ocean Modeling* on the Arctic Ocean at the end of 2013. Therein, a waves-in-ice model (WIM) was developed that advects a unidirectional wave spectrum into and within an inhomogeneous ice cover under the

influence of a conservative scattering process collinear to the incident wave train. A parametrization of wave-induced ice breaking was also included in the WIM.

Building upon Williams et al. (2013a,b), our work will enhance the way wave-ice interactions are absorbed into WIMs and ice/ocean models. Three avenues are currently being investigated that will each be included in a new 2D WIM in due course: (i) an augmented scattering model that considers the directional evolution of ocean wave spectra and their spreading due to the presence of the fragmented ice cover; (ii) an improved parametrization of wave-induced ice breaking under realistic irregular wave spectra; and (iii) a parametrization of non-conservative wave-ice interactive processes that dissipate wave energy in the ice-covered ocean. Feeding into the long-term goals of the current project, the WIM developed as part of the WIFAR project is independently also being integrated in Arctic Basin scale operational forecasting and global models.

A new 2D scattering model has been developed, which replicates the way ocean waves and sea ice floes interact in Nature. The model subdivides the ice field (composed of a large but finite number of floes) into contiguous "slabs" (strips) of designated finite width running parallel to the ice edge, with each slab containing a random distribution of circular ice floes. The FSD in each slab may be generated from a random sampling of floe diameter and thickness, parametrized by ice concentration and observed statistical power law distributions. Our aim is to characterize the evolution of a monochromatic directional ocean wave spectrum fully as it makes its way in an ice-covered ocean with specified (observed) mean properties. The new *slab-clustering method* offers significant improvements in terms of computational efficiency for the solution of the multiple scattering problem, as described technically by Montiel et al. (submitted). It also provides a natural framework to track the evolution of directional wave properties with distance from the ice edge as recently reported by Montiel et al. (2014) prior to submission of a substantive manuscript to *Journal of Fluid Mechanics*.

We characterize wave energy attenuation and directional wave spreading by estimating the angular spreading function between the slabs. Assuming that the ice edge is perpendicular to the x-axis (without loss of generality), the directional wave spectrum may be described by

$$E(x,\theta) = E_0(x)\mathscr{S}(x,\theta),$$

where $E_0(x)$ is the total energy and $\mathscr{S}(x,\theta)$ is the angular spreading function with unit energy. At a distance x from the ice edge, attenuation and directional spreading are given by

$$E_0(x) = E_0(0)\mathrm{e}^{-\alpha x} \quad \text{and} \quad \mathscr{S}(x,\theta) = \int_{-\pi}^{\pi} f(x,\theta,\theta')\mathscr{S}(0,\theta')\mathrm{d}\theta',$$

with $f(x,\theta,\theta')$ a function characterizing the directional spreading of an arbitrary wave field in the system. Exponential attenuation of the wave energy is then parametrized by a single attenuation coefficient α, similarly to the 1D scattering model. An appropriate parametrization of the function f is now also required to assimilate the effects of directional spreading in the WIM. Our approach consists of using the slab-clustering method for ensembles of random realizations of the MIZ defined by a prescribed FSD. Ensemble averaging then allows us to fit a simple model to the spreading observed. A hitherto untested candidate for this model is

$$f(x,\theta,\theta') = A + B\cos^{n/x}\left(\theta-\theta'\right),$$

which would require estimating 3 parameters A, B and n. To implement this improved parametrization of scattering in the WIM, we will generate look-up tables for the 3 parameters that will depend on wave period, ice concentration, mean floe size and mean floe thickness.

Aside from a small number of ad hoc field experiments, there have been few in situ data collected relating to wave-ice interactions since the MIZEX campaign of the 1980s. This DRI and the associated 'Emerging Dynamics of the Marginal Ice Zone' DRI have fieldwork planned that has the capacity to generate significant new data that will intersect appreciably with the modeling work that is being synopsized herein. Laboratory experiments such as those reported by Montiel et al. (2013a,b) and some recent ones concerned with water wave transmission past a solitary sheet of floating plastic with prescribed physical properties and by an array of floating disks, potentially provide a rich source of data to test models. While scaling creates major challenges for this type of work, the data sets produced are invaluable. Other laboratory experiments presently being discussed by DRI participants may aid our understanding as well, e.g. those planned for the Hamburg Ship Model Basin.

Benefiting from the better technology and analysis tools available now, field experiments supported by an intensive remote sensing program coordinated by Holt at JPL and involving both airplane and satellite data, will furnish a unique set of measurements that will allow validation of theoretical models and provide quantities for parametrizations. IceBridge flights to include the Airborne Topographic Mapper, the Snow Radar, and DMS imagery have been requested to support the Sea State DRI field campaign by Holt. Together with a graduate student supervised by Shen, Holt has also been working with legacy aerial photographic data and recent spaceborne fine-resolution optical imagery to understand how FSD matures in the presence of a wave field. This information is crucial both as an input to our modeling work, and to validate it.

In the last report, we presented some preliminary model results Arctic wide, based upon an extrapolation of the Fram Strait study reported by Williams et al. (2013a,b). The full Arctic model now runs well and Williams has tested it by inputting full frequency wave spectra as opposed to using only the significant wave height H_s, the peak period T_p and the mean wave direction. Our approach in the immediate future will be to set up and further advance the framework by employing the simpler Meylan and Masson (2006) model for the evolution of a directional spectrum, implement the radiation stress calculation and add this stress to the wind and ocean stress in the dynamic equations for the ice. While this last step can be implemented independently of an accurate directional scattering module, it would be less meaningful since it wouldn't conserve energy. Look-up tables that encapsulate the predictions of the slab-clustering model will thus be accommodated in the framework to conform to the requisite physics.

Williams and Squire (2014) investigate wave-induced ice breakup from the perspective of building a parametrization of the length dependence of strains in a 1D ice floe. While more work is necessary, e.g. on the effect of Young's modulus on the reflection coefficient, our aim is to include this and a simple parametrization of the strain-floe-size relationship in the 1D WIM. Evidently, this all remains work under way towards the longer term goal of inserting the 2D WIM described above into the TOPAZ framework and, by so doing, enabling fully directional seas generated by WAVEWATCH® III or from experimental data to be input. Addition of ocean wave impacts to full scale climate models is also planned, for which Bennetts and Squire developed a low-cost numerical method to determine the FSD produced by an incident wave field in coupled wave/sea ice models (Bennetts et al., 2014a). The method alleviates the need to use high-resolution subgrid meshes for wave-ice models when embedded in large-scale wave and/or sea ice models. Bennetts, Squire and colleagues use the method to integrate a model of wave-induced ice fracture into a standalone version of CICE v4.1 in the Antarctic (Bennetts et al., 2014b). Further developments and analysis are ongoing.

The WIM developed by Williams et al. (2013a,b) can be extended to include additional physical

non-conservative processes. Dissipation of wave energy in the MIZ is controlled by many nonlinear phenomena that are not represented by a conservative scattering formulation. Our approach will parametrize dissipative effects by modeling the physical processes of interest in a simple setting. Several processes are currently being investigated: collisions between floes, overwash, inelastic deformation of the ice layer and turbulence in the water, e.g. at the corners of floes. In due course, sensitivity analyses of these models will then be conducted to generate lookup tables used in the WIM.

WORK COMPLETED

To the 30th September 2014, the following accomplishments can be reported as part of project N00014-131-0279:

- **Directional wave scattering.** A method was developed to simulate the propagation of directional wave spectra in large random arrays of scatterers (led by the PI and postdoctoral fellow Montiel). The so-called slab-clustering scheme allows the directional properties of a wave field to be tracked deterministically through large arrays of scatterers with random sizes. Due to its potential impact in several areas concerned with wave scattering (e.g. acoustics, electromagnetism, hydrodynamics), a paper describing the method for a canonical related acoustic problem has been submitted for publication in *SIAM Journal on Applied Mathematics* (Montiel et al., submitted). The method was validated by comparison with the infinite multiple-row array method of Bennetts (2011) in the case of regular arrays.
- **3D model for wave scattering by ice floes.** A 3D model for wave attenuation and directional spreading in the MIZ due to 2D conservative multiple scattering has been devised, utilizing slab-clustering grounded in the mathematics outlined by Montiel et al. (submitted). An example of its use is provided in figures 1 and 2, which show how a simple monochromatic wave train with power cosine spread is attenuated and redistributed angularly as it travels through a 15-km-wide swath of more than 2500 ice floes. The aim of the numerical experiment was to replicate work done at the end of MIZEX, which observed that the seas entering an ice field become directionally isotropic as they penetrate farther into the MIZ with the distance to full isotropy depending on the wave period. Figures 1 and 2 appear to reproduce the field data at least qualitatively, which is reassuring given the paucity of morphological data collected during the field experiment. The solution for a single slab was investigated thoroughly due to its relevance in the study of ice edge bands. The findings of this investigation were reported in a paper presented at the ‘International Symposium on Sea Ice in a Changing Environment’ in Hobart and submitted for publication in *Annals of Glaciology* (Montiel et al., in press). The full-scale model was implemented and tested for realistic ocean directional wave spectra in a MIZ with random FSD. Preliminary results for attenuation and directional spreading were presented in the conference proceedings paper by Montiel et al. (2014).
- **Validation of the Williams et al. (2013a,b) 1D WIM.** A paper seeking to validate the Williams et al. model against data is currently in preparation, led by the AI, Williams, and the PI, Squire. Simulations have been performed over a short period in September 2013 when a ship was near the Greenland Sea ice edge with Williams aboard. The analysis is supported by two types of passive microwave imagery to provide concentration, high resolution SAR imagery, the usual atmospheric, ocean and ice inputs, plus WAM significant wave height and peak period. The SAR allows predictions of MIZ width and other parameters to be verified. This is done in figure 3. It is evident that the resolution of the concentration field provided by passive microwave data is vitally important and that the $> 20\,\text{km}$ resolution typical until fairly recently produces results for MIZ width that are

quite different from the high resolution product and what is seen by the SAR.

- **Wave tank experiments.** Using the University of Plymouth's new directional wave basin facility in collaboration with other DRI scientists, Bennetts conducted a series of laboratory experiments to validate existing models of wave interaction with a single "synthetic" ice floe for different thicknesses and material moduli. Floe motion was measured using the Qualysis non-contact digital video motion capture system, while wave probes measured reflected and transmitted wave fields. Although the motions of the floe itself seemed to fit linear theory, transmitted waves could be nonlinear, i.e. amplitude dependent, at times for certain experimental arrangements; an important finding apropos how wave energy is reduced in MIZs.

  In July 2013 a wave-tank experiment was carried out at a large wave basin facility at Océanide in France by AIs, Williams and Bennetts, which looked into wave attenuation by the MIZ and drift motion in the presence of currents and waves. A paper describing this work and the ensuing analysis was recently sent off to a journal. In the wave attenuation experiments, low and high concentration arrays of 40 and 80 "ice floes" (0.99 m diameter wooden disks) were moored with springs to the tank floor and plane waves were sent down, with an array of wave probes to measure the reflected and transmitted waves and accelerometers to measure floe motion. The data analysis conducted during the past year shows good agreement with theory at low concentration but inferior agreement at high concentrations where collisions and overwashing of the floes has an effect. Evidently the ice edge region will be most affected.

  Although not formally part of project N00014-131-0279, data from these experiments form a valuable addition to verifying theoretical predictions. For example, a conclusion of the latter study is that, while 1D scattering can certainly be tuned to reproduce elements of the laboratory data, the directional scattering approach of Meylan and Masson (2006) has the benefit that it is easier to distribute the scattered energy into other directions to allow momentum flux to be used to calculate radiation stress. This can then be taken into account, along with wind and current, to move the sea ice around.
- **Wave attenuation experiments.** The joint experiment between Martin Doble and NERSC (Yngve Kristoffersen), which took place from 25 July to 6 August 2013 just before the start of the reporting period, collected no data but was a good test of equipment. Somewhat unexpectedly for the Greenland Sea, there were no waves! Bennetts, with a colleague from another DRI project (Meylan), has reanalyzed some data collected in the Southern Ocean MIZ in 2012 and found that the average attenuation rates of the spectral components of the wave field are proportional to the reciprocal of wavelength (Meylan et al., 2014). This is consistent with earlier results in the Labrador Sea (Wadhams, 1975).
- **Dissipative processes.** (i) A comparative analysis of wave propagation properties between the viscoelastic layer model of Wang and Shen (2010) and the standard thin elastic plate model augmented by an energy dissipative loss modulus is currently being conducted by PhD student Mosig. Very promising results suggest that the more complicated Wang and Shen dispersion relation can be replaced by a much simpler one which is numerically expeditious to solve – especially in the deep ocean – so its use in WAVEWATCH® III can be made more efficient with less code furcation. But, more significantly, this constitutes the first step towards using our scattering model to calibrate the viscoelastic moduli parametrizing the ice layer. (ii) Modeling of wave energy dissipation due to surge induced collisions and overwash is led by Bennetts and PhD students, along with laboratory experiments with Meylan to supplement the modeling study which show that collisions are strongest and most frequent for mid-range incident wave periods and large amplitudes (Meylan et al., 2014). (iii) Artificial dissipation based on a limited-range scattering approximation described in last year's

report was implemented in the scattering model, but did not provide the expected outcome on wave dissipation. This approach has therefore been abandoned.

RESULTS

After 21 months the major outcomes from the project are

- final completion of the Williams et al. (2013a,b) papers, with publication in November 2013 in a special issue of *Ocean Modeling* targeted on the Arctic Ocean;
- modification of the WIM code to be Arctic wide, primarily due to Williams – a named AI on project N00014-131-0279 who is supported by ONR Global;
- modeling of the reflection and transmission of an incoming directional wave spectrum by a solitary ice edge band (a precursor to using a multiple band model for a larger scale study), which involved comparisons with field data and was reported in Montiel et al. (in press);
- development of the slab-clustering scheme for multiple scattering by large random arrays of obstructions, including redaction and submission of a paper (Montiel et al., submitted), primarily due to Montiel with direction from the PI and AI (Bennetts), as required;
- implementation and testing of a grid size conservative model for attenuation and directional spreading of wave spectra in the MIZ, based on the slab-clustering method (Figures 1 and 2 reproduced from Montiel et al. (2013c) and Montiel et al. (2014)), led by Montiel with geophysical direction from the PI;
- preliminary results relating to (i) assimilating the MIZ in climate models (Bennetts et al., 2014b), and (ii) more efficient ways of computing the strains in ice floes arising from wave-induced bending and incipient breakup (Williams and Squire, 2014).

To a degree, the massive adjustments that the æstival Arctic sea ice has experienced since at least the beginning of the satellite era are believed to be caused by ice-albedo temperature feedback. Notwithstanding this, as the Arctic opens up to become more MIZ-like, the PI has suggested that ocean waves will have a much greater prominence that can nourish the feedback by breaking up the sea ice to create more open water and moving ice floes about. Waves can also now be generated within the Arctic basin to a much greater extent as the aggregated fetch lengths are longer (Thomson and Rogers, 2014), and global wave heights are larger (Young et al., 2011). These statements, together with the performance of climate models in predicting the rate of disappearance of Arctic sea ice (Jeffries et al., 2013), have sparked interest in the sea ice community, with the result that the PI has given six invited keynote addresses including and since the 2013 AGU (Squire, 2013, 2014a,b,c,d,e) based upon project N00014-131-0279 research outcomes.

IMPACT/APPLICATIONS

The primary impact of the research outcomes from this project relate to better forecasting of Arctic and Subarctic sea ice conditions, as a major deficiency in the current models being used, namely the absence of destructive ocean waves, will be overcome. Oceanic GCMs and fully coupled climate models will also benefit, for although direct ocean wave effects are unlikely to be subsumed in global scale simulations because of the models' large demands on computing resources, FSD and MIZ width can potentially parametrize the involvement of waves.

RELATED PROJECTS

The now completed WIFAR project, http://www.nersc.no/project/wifar, led from NERSC and funded primarily by the Research Council of Norway, involved many of the scientists participating in project N00014-131-0279 and grew directly into it. The July 2013 wave-tank experiment mentioned above was supported by Total E&P. The SWARP (Ships and Waves Reaching Polar Regions), http://swarp.nersc.no/, is a NERSC-led project funded by the European Union FP7 programme, which now partly supports Williams, an AI on the current project, with remuneration that takes his salary to 1 FTE. SWARP will develop downstream services for sea ice and waves forecasting in the MIZ in the Arctic, integrating new met-ocean services into software for contingency planning and onboard navigation. Each of these research programmes contributes positively and synergistically to the current project.

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Invited talks presented during the reporting period

Squire, V. A. On impacts of ocean waves in marginal ice zones and their repercussions for Arctic ice/ocean models. Invited plenary presentation, *American Geophysical Union (AGU) 46th Annual Fall Meeting*, San Francisco, USA, December 2013.

Squire, V. A. Why ocean waves propagating in ice-covered seas have suddenly become fashionable. Invited plenary keynote presentation, *KOZ Waves: Kiwi-Oz Waves Conference*, Newcastle, Australia, February 2014a.

Squire, V. A. On impacts of ocean waves in marginal ice zones and their repercussions for Arctic ice/ocean models. Invited plenary keynote presentation, *International Glaciological Society (IGS) International Symposium on Sea Ice in a Changing Environment*, Hobart, Australia, March 2014b.

Squire, V. A. Contemporary advances in ice/ocean models and OGCMs via the assimilation of ocean waves. Invited plenary presentation, *Sea-Ice Mechanical Modeling: From Physics to Applied Mathematics*, Grenoble, France, June 2014c.

Squire, V. A. Ongoing development of ice/ocean models and OGCMs: a case for including ocean wave interactions. Invited plenary keynote presentation, *22nd IAHR International Symposium on Ice*, Singapore, August 2014d.

Squire, V. A. Perspectives of ocean wave / sea ice connectivity relating to climate change and modelling. Invited plenary keynote presentation, *Royal Society of London Conference on Arctic Sea Ice Reduction: the Evidence, Models, and Global Impacts - Further Discussion*, Chicheley Hall, Buckinghamshire, UK, September 2014e.

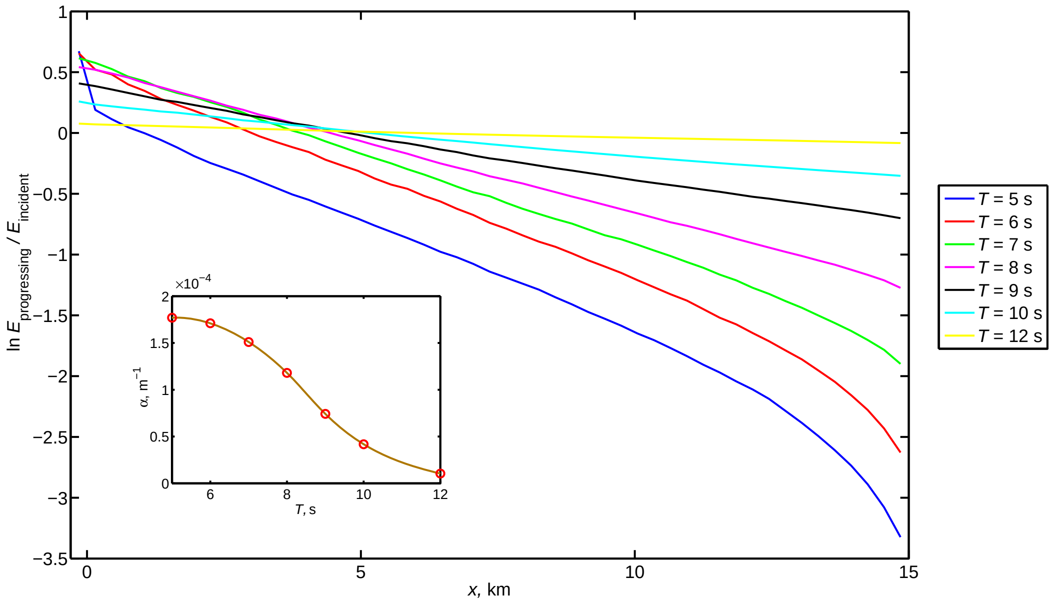
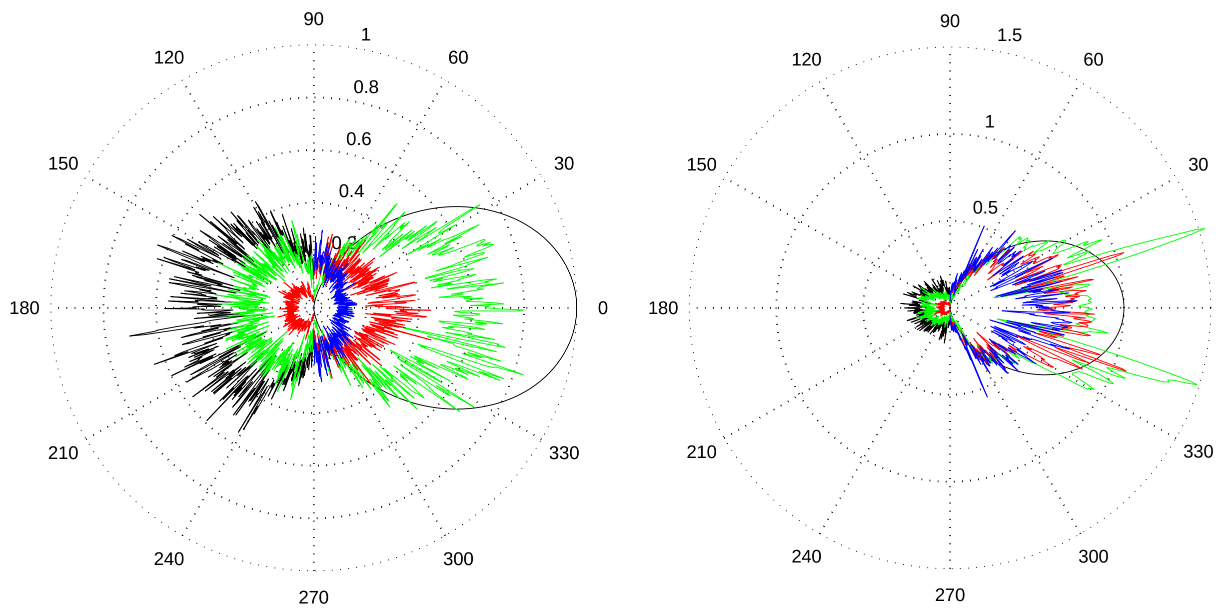


Figure 1: Exponential attenuation of wave energy in a MIZ composed of 2550 floes with random FSD. Results are averaged from an ensemble of 30 simulations. (a) Natural logarithm of the wave energy through the MIZ for wave periods $T = 5$–12 s. The attenuation coefficient is then plotted against period in sub-plot (b).



(a) (b)

Figure 2: Directional spreading of wave energy in a MIZ of width 15 km composed of 2550 floes with random FSD. Results are averaged from an ensemble of 30 simulations. Polar plots of wave energy are given at 0 km (black), 3 km (green), 9 km (red) and 15 km (blue) from the ice edge, for wave periods (a) $T = 6$ s and (b) $T = 10$ s.

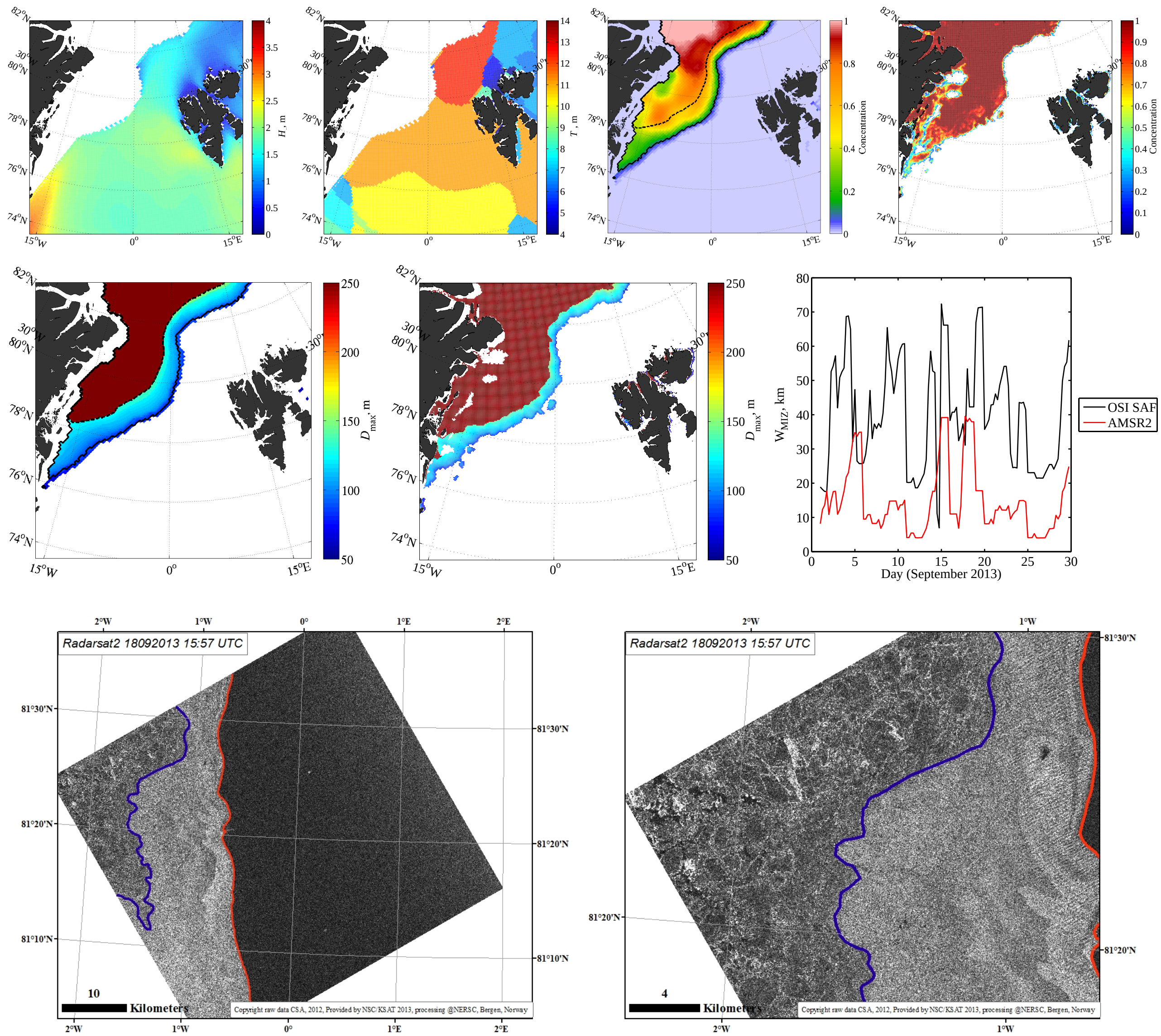


Figure 3: Upper panels show inputs. Left two panels are SWH and peak period inputs from WAM wave model; right two panels are low resolution (>20 km) OSI SAF and high resolution (4–5 km) AMSR2 concentration inputs for the same period. Middle panels show model output maximum floe diameter from OSI SAF and AMSR2 concentration inputs. Differences are shown in time series on the right. Lower panels show Radarsat2 SAR imagery (Courtesy Mohamed Babiker, NERSC) on 18th September 2013. Ice thickness is 1.5 m.